Organic Photovoltaic Cells:
A Set of Lessons and Activities for Three Age Groups

An Honors Thesis (HONR 499)

By

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Abstract

Science is continuously aiding us in developing new technologies we use in our everyday life, but STEM fields are not producing enough graduates to meet the demand. Science experiments that are not only interesting, but also have real-world applications and geared to younger students and non-science professionals are hard find in the literature. In the science activities that follow you will find age-appropriate technical background, the activity procedure, prepared worksheets, and a description of material safety. This thesis was done with the hope that any teacher or interested person could understand the activity and convey the ideas behind it to others.

Acknowledgments

I would like to thank Dr. Patricia Lang for advising me on this project and agreeing to it in the first place. She has pushed me harder than I would have pushed myself, and I came out better for it. Her help this past year on this project and other things was most welcome, and I am glad for her guidance through my years here.

I would like to thank Kyle and Mikaela for encouraging me to keep going through all of the rough spots during this time and for helping me overcome this challenge.

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Process Analysis Statement

When I was very young, I learned that science and education are both very important. My dad is an electrician and my mother has a master's degree in mathematics. My father's sister has a degree in engineering, and of my mom's three sisters, two teach elementary education (one holding her master's in education) and the other has a master's degree in geology. My mother's brother used to work for NASA. I was also blessed with teachers who wanted to get my classmates and me interested in science from a very young age. Because of the people in my life, I originally came to Ball State University as a physics education major, wanting to share my passion for science with future generations.

Due to scheduling conflicts my first semester here, I changed my major to general physics and professional chemistry. Switching majors, however, did not change my perception on the need for effective science teachers. It did change my thoughts on how much influence just a teacher can have though. When a child only has a teacher, whom they see for less than seven hours a day, pushing them to explore and learn, the child will rarely pick up an interest. Scientific illiteracy is plaguing society at all levels, and as a future science professional, that is very disturbing. I wanted to create something that could influence children and adults to investigate science by doing more than just scratching the surface like many activities do, and possibly even lead them to consider or choose a STEM path for themselves.

Another large reason why I wanted to create an engaging and socially-relevant activity is because of my younger brother, who is currently in third grade. His mother, my stepmother, never graduated college and due to disagreements in the family, he never sees my dad's sister. The only science-minded person he has is my dad, because I live so far away. My brother also has different teachers than I did when I was at the school he currently attends, and I don't know how much or what kind of science they explore.

Through creating these activities, I learned quite a bit more than I expected. If every lesson plan puts a teacher through as much stress as this project did for me, I don't have a clue how they start their career. It was challenging to find a project that was based on contemporary chemistry that didn't utilize large instruments or toxic chemicals and could be explained to both elementary children and college-aged adults. If at least one person finds the information collected and presented here helpful, then my goal is accomplished.

Motivation

When you ask a child what they think a scientist looks like, it usually consists of a lab coat and crazy hair while mixing a glowing tube of sludge with something to make it another color. The child's perception of a scientist is one that has both the capacity to save and destroy the world, depending on how the child was raised to view science. According to Carla Morais, the image of this scientist won't change from age 9 or 10 until the child is in secondary school, usually after taking a hard science class.(16) The current-day scientist isn't the person in the mind's eye of a child, but they are just as important. Scientists are making leaps and bounds in the progress toward renewable energy(2), modern medicine(5), sustainable agriculture(4), and even extraterrestrial exploration(9). But with the stereotype of a mad scientist who spends all of their time alone in a lab, many children don't think about science as an appealing future for themselves. This is a real problem because degrees in sciences, technologies, engineering, arts, and mathematics (STEAM) are some of the largest growing and looked-for degrees for lifelong careers.(19, 34)

In Sarah Windsor's article "Impact of Chemistry…" she shows that the attitude of students toward sciences are made up by the eleventh year of schooling.(32) According to Clarisse Habraken, a large part of why students do not pursue science, specifically chemistry, is because the subject matter is not related to what is going on around them in the real world, and students therefore do not see the use of chemistry.(7) Relating chemistry to the real world is a big problem, because the students need to learn the basics before they can jump into a project with the more complex chemistry that are used in industrial applications, says Kearen Evans.(6)

The easiest solution is to intrigue children at a young age and to develop their passion for science so that it is strong enough for them to get through the necessary background without losing heart. But, what exactly is out there for children to do that sparks their interest? A quick Google search for "chemistry projects at home" will yield thousands of results, some with a lesson attached and others that just look cool. Many of them, such as the experiments described in "'Having a Ball with Chemistry': More Things to Try" are temperature dependent studies that look cool(12); but we can control temperature, so how does that lesson relate to contemporary uses of chemistry? There are also fun activities that use ingredients like vinegar and baking soda to 'explode'; five of which can be found in Angela Thayer's "Fizzy Fun (5 Baking Soda Experiments)".(3, 31) Who doesn't like explosions? But again, chemists nowadays are preventing explosions more than creating them.(20)

Sometimes you will find one or two activities that relate to current societal issues. One of the most current home experiments you can find is how to create your own solar cell from berries, which will engage participants of all ages; see Figure 1 for a simple schematic. As the world comes to the realization that our petroleum and natural gas sources are running low(14) and that it is time to find a better solution, the importance of finding and utilizing renewable energy is becoming more apparent.(13, 18, 23) Pretty soon, solar cells are going to be everywhere, and chemists are

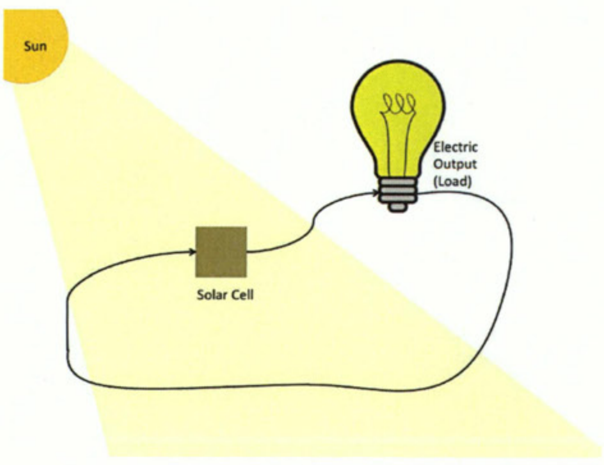


Figure 1: Simple schematic of a solar cell circuit appropriate for a grade school activity

continuously exploring new paths to attempt to make solar energy more efficient and cheaper.[2, 13, 18, 21] The activities presented here, which are designed around creating and testing a solar cell, are one way to get children and young adults interested in chemistry, and the experiments will enable them to see the investigative side of the sciences.[7, 16, 32]

I aim to modify an organic solar cell assembly experiment[10, 33] for three levels of instruction - grade school (4th - 7th), high school (9th - 12th) and college (introductory chemistry) - so that any classroom teacher for these groups could easily understand, develop, and convey this real-world application of chemistry. See Figure 2 for a schematic of the solar cell.

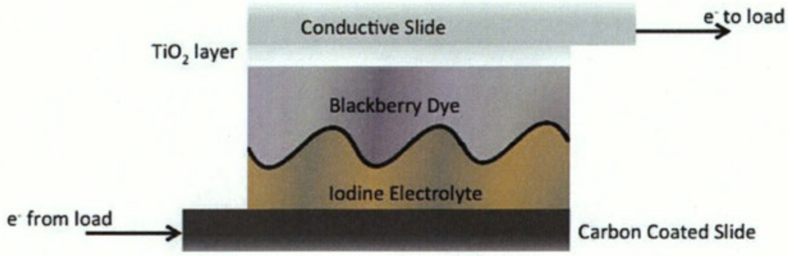


Figure 2: Schematic of the solar cell used in the high school and college activity

Introduction

In the grade school activity that follows, we focus on the simplest of theory based on an analogy to plants using the sun's light to produce energy. This method uses a prepared kit assembly[8] and simple electronics to test. In the high school activity we expand the topic by including the idea of photons and electrons. In this activity, the cells are not made from a prepared kit and participants will make their own solar cells described in Jill Johnsen's article "Juice from Juice". [10] In the college level activity, the idea of excitons, electron and electron hole pairings is explored, and photons are expanded upon; however, the same experimental procedure as the high school activity is used.

Activities for Elementary School Students:

Making Light with Berry Juice

Introduction/Background:

As solar energy is quickly making strides to becoming more popular, efficient, and more available, kids will see more and more about this source of energy.(3a) There are many different types of solar cells and solar energy, but to children who are still very fascinated with the natural wonders of the world, they will most easily relate to organic solar cells. Organic solar cells are solar cells that use an organic (carbon-containing) substance to transport electrons in a circuit to produce electrical energy.(4a) This is very similar to chlorophyll in the production of energy for the plant and for whatever consumes it. Electrical energy is produced from the solar cell when light energy from the sun is changed by the organic dye.

Figure 3: Trees get their energy from sunlight

Figure 4: Rooftop solar panels could power an entire community

This activity outlines a project and lesson plan around an organic photovoltaic cell. The organic solar cell is available for purchase from the Institute of Chemical Education's catalogue at ice.chem.wisc.edu. While the photovoltaic is in the dark, the electrons occupy a low-energy state known as the valence band, but when the cell is in sunlight, the energy from the light excites some of those electrons into a high-energy state known as the conductive band. Those electrons can then move to another atom or molecule, and that movement creates a current.[1a, 4a]

The organic photovoltaic cell used in this procedure consists of titanium dioxide with blackberry juice concentrate, and a solution of iodine and triiodide.

Engaging the Students:

To help a child learn about how the sunlight has energy, ask whether they get hot or cold when they stand in sunlight.

The solar cell they are building mimics the process of photosynthesis that occurs in plants.

Titanium dioxide is in white paint and many other common materials.

Iodine is the stuff they use to clean your skin that turns it yellow.

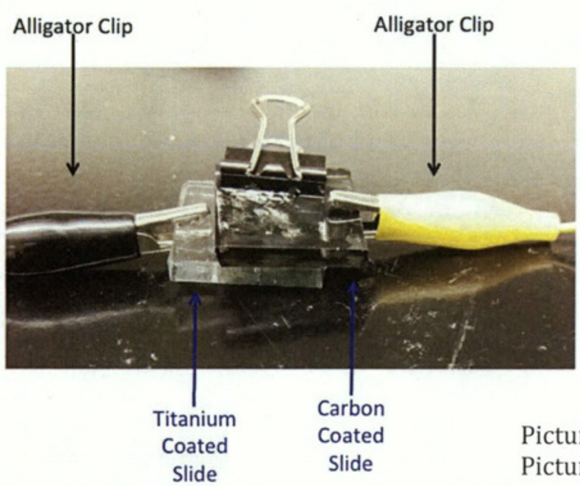
Procedure:

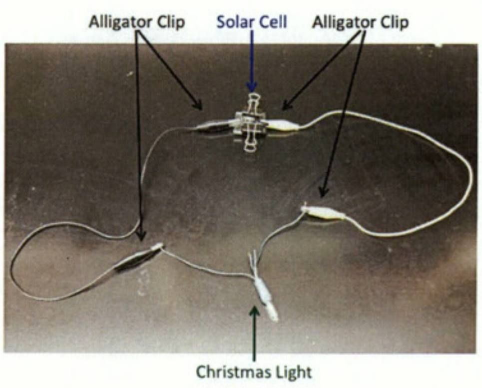
Follow the instructions included in the kit to assemble the solar cells.

For the full procedure, see *Juice from juice* by Jill Johnsen and Stephanie Chasteen.

To attach to electric items:

1. Attach one alligator clip to each slide of the cell where no overlap occurs.
2. Attach the other end of each alligator clip to a single wire on the device to power.

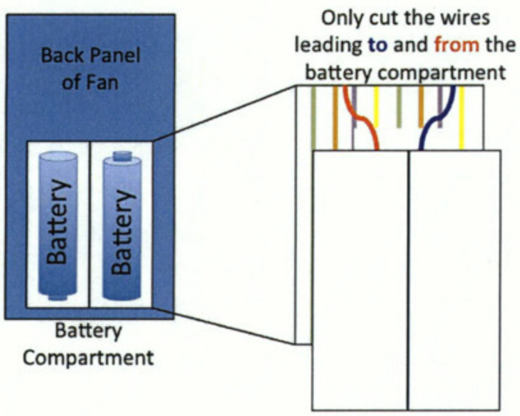


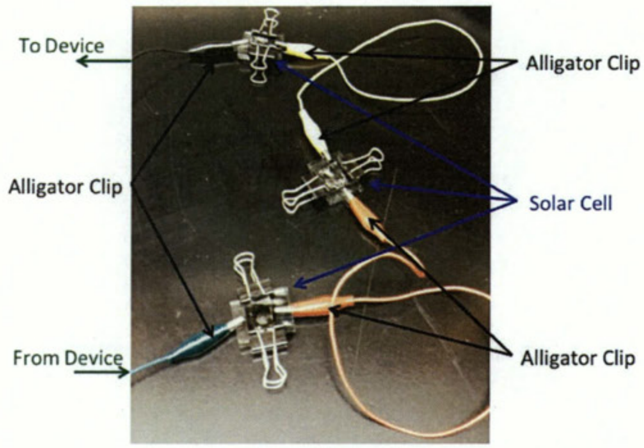


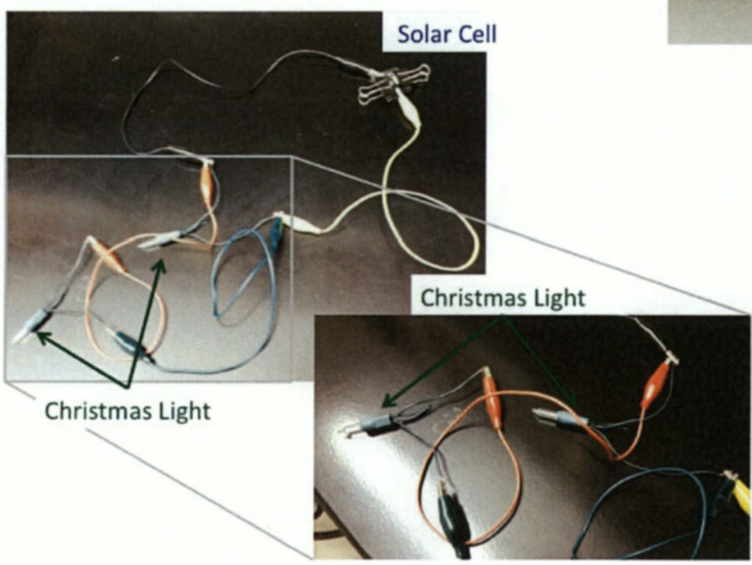
Picture 1 (left): Side view of connected alligator clips to solar cell.
Picture 2 (right): Circuit with a single light and solar cell.

When connecting multiple cells together:

1. Attach one alligator clip from the first cell to the alligator clip of the second cell with opposites connecting (carbon-coated side to TiO_2 side)







Picture 3 (top left): Remove the battery panel and cut the two wires leading to and from the battery compartment.
Picture 4 (top right): Multiple solar cells connected in series leading to fan or other device.
Picture 5 (left): Two lights connected to a single solar cell and closer view of connectivity of lights.

Experimental Notes:

- To maximize the student involvement, the titanium dioxide paste can be applied a day prior to use, but you should heat the slides for them.
- Graphite sticks will work fine, and the children use those, but if you don't have access to a graphite stick, you will need to cover the slide with soot by holding it over a candle.
- Premix the iodide electrolyte solution, and store in a dark or opaque bottle.
- Let the kids squish some blackberries. It's fun!
- When trying to power larger items, such as a small fan, have the children attach their cells in parallel and series. Series will work more efficiently.
- You can also power a few Christmas lights in direct sunlight. Take an old set of lights and cut each bulb socket away from the others. If there are a total of four wires from the socket, then strip one from each side so that the wires are exposed. Depending on the voltage reading, you can power 2-4 lights with one cell. (This is only for direct sunlight.) If you have any other small electric items, try to power those as well.
- If using a flame to sinter instead of an oven, be careful. Some slides will shatter if heat is too concentrated in one spot.
- The slides read between 9.3 and 13.7 ohms before starting the experiment.
- In indirect sunlight, cells read between 0.47 and 0.13 volts.
- In direct sunlight, cells read between 0.82 and 0.25 volts.
- If the cell is reading below .24 volts, it will not be able to power a Christmas light.
- Place the cells in series to power larger objects.
- Place lights in parallel to power multiple at once.

Questions to Ask:

Question: Where is the energy coming from, and what kind is it?

Answer: Sun, light

Question: How many lights did your cell power?

Answer: 2-4

Question: Which way of connecting our solar cells worked better?

Answer: Not side by side (parallel), but one after another (series)

Question: Did the light or the fan use more energy? How do you know?

Answer: The fan. It took more of them to work

You can relate that back to plants if you like, by asking how much energy does a tree need compared to a flower and things like that.

Prepared Worksheet and Answer Key Follows:

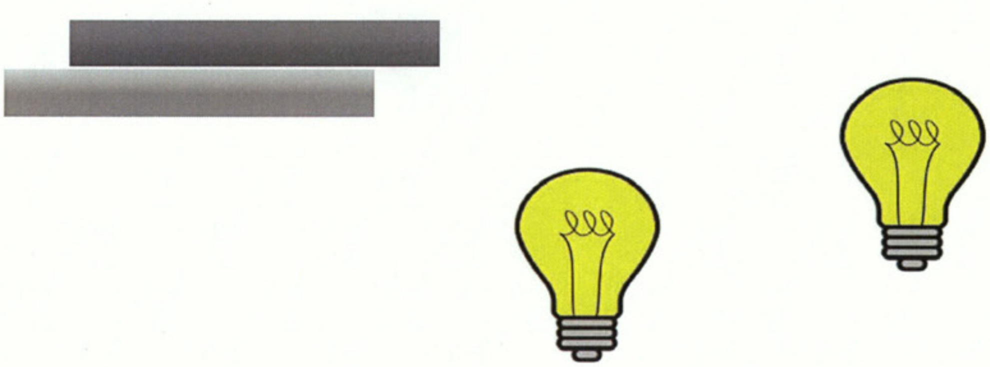
Name____________________

1. Where did the energy come from?

2. Draw how you connected the light and the solar cell.

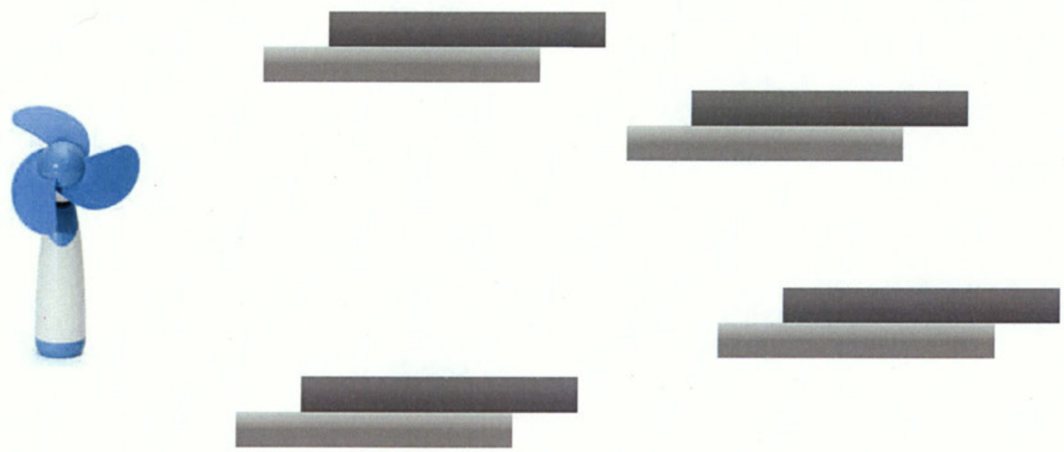
3. Connect the lights and solar cell with more than one light

bulb.



4. How many lights did you power?

5. Connect the solar cells with the fan.



6. What took the most energy?

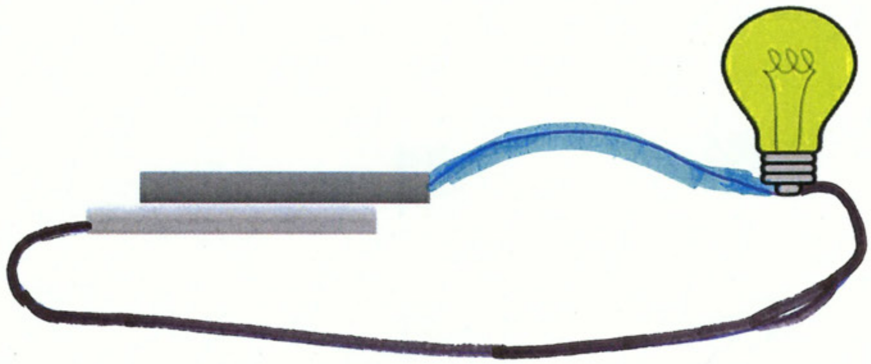
7. What else gets energy from the sun?

Name Key

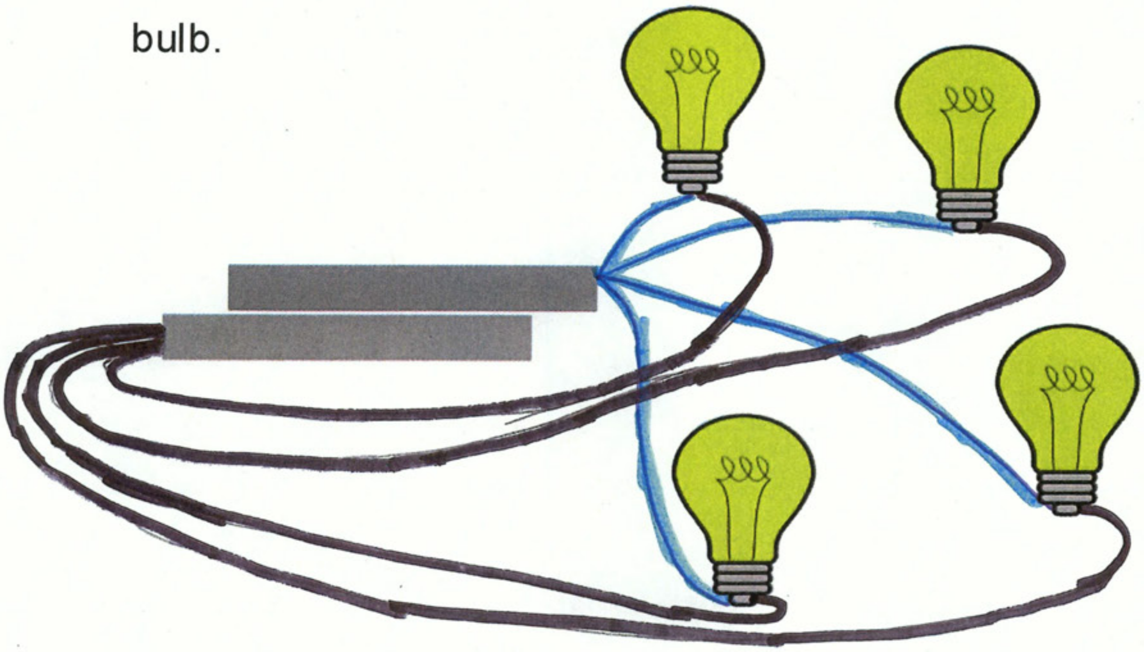
1. Where did the energy come from?

the sun

2. Draw how you connected the light and the solar cell.



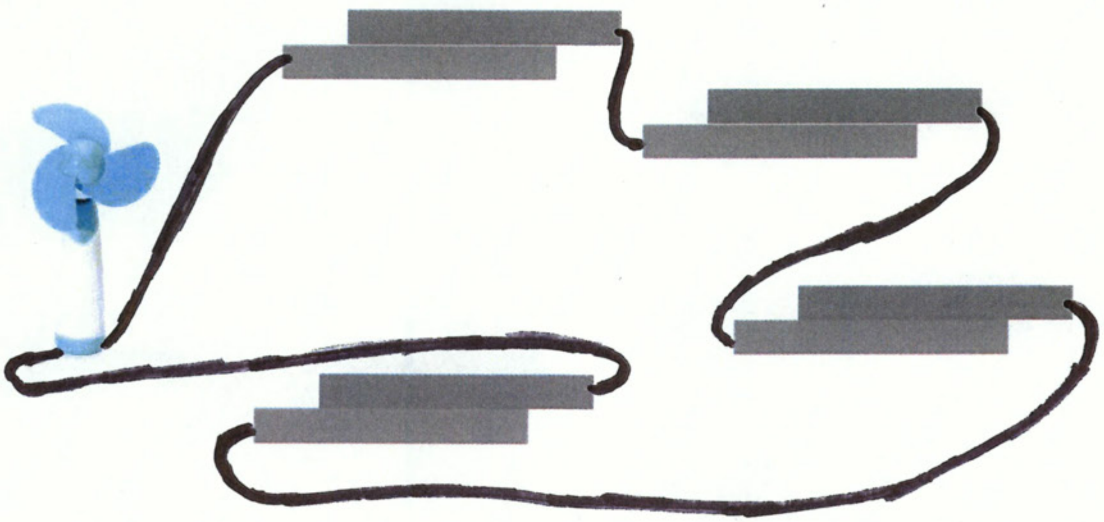
3. Connect the lights and solar cell with more than one light bulb.



4. How many lights did you power?

4

5. Connect the solar cells with the fan.



6. What took the most energy?

the fan

7. What else gets energy from the sun?

plants (trees, flowers, grass)

Safety and Storage:

- Do not let children near open flames or extreme heats.
- If any of the participants is allergic to raspberries/blackberries, do not attempt this cell. There is a kit by the Institute for Chemical Education (the same source for the organic kit described here) that is a nanocrystalline solar cell instead of an organic cell. It uses a similar iodine solution, so children allergic to iodine cannot make either of these options.[2a]
- Titanium dioxide is a slight skin irritant, wash with soap and water. If it is in contact with eyes, flush them with cool water immediately. Store in a cool dry space.[9a]
- Ethylene glycol is a slight skin irritant, wash with soap and water. Flush eyes with cold water if contact is made. If ingested, call a physician immediately. Store away from heat sources in a sealed container in a dry space.[6a]
- Potassium Iodide is a slight skin irritant. It should be stored in a dark or opaque container that seals tightly and keep in a cool environment.[8a]
- Iodine is extremely hazardous if it comes into contact with skin and eyes. Do not store above 77 degrees Fahrenheit in a tightly sealed dark or opaque container.[7a]
- Ethanol is slightly hazardous as a skin and eye irritant and should not be ingested. Do not store above 73.4 degrees Fahrenheit, and keep sealed and away from all sources of flame. If possible, store in a fire resistant space away from other materials.[5a]

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6a. ScienceLab.com. MSDS Ethylene Glycol https://www.sciencelab.com/msds.php?msdsId= 9927167

7a. ScienceLab.com. MSDS Iodine https://www.sciencelab.com/msds.php?msdsId=9927547

8a. ScienceLab.com. MSDS Potassium Iodide

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https://www.sciencelab.com/msds.php?msdsId=9925268

Activities for High School Students:

Power from the Sun: Making a Solar Cell

Introduction/Background:

The sun's energy is one that we have started to harness in the last century, and we still are not great at it. Our best solar cells have a conversion rate of less than 50% according to Macdonald's article "Engineers Just Created the Most Efficient Solar Cells Ever"[5b], and those are the high maintenance cells that are out of most people's price range. As solar energy is quickly making strides to becoming more popular, efficient, and more available, everybody will see the advantages of using this source of energy.[6b] There are many types of solar cells, the most common being a crystalline-silicon photovoltaic cell[4b, 13b], but the one outlined in this activity based on "Juice from Juice" by Johnsen and Chasteen is an organic photovoltaic cell (OPV)[3b], which means the activated material is a carbon-containing substance. OPVs are cheaper to produce than nanocrystalline photovoltaic cells and use more abundant materials in their production.[7b] Because of the relatively low cost, the OPVs have some of the largest potential to grow.[7b]

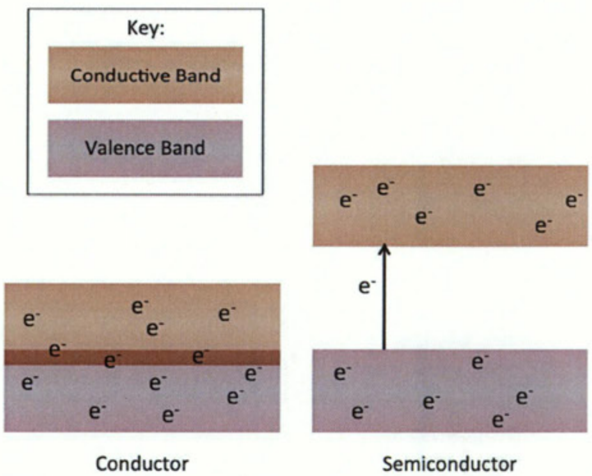

Figure 5: Energy gaps between the valence band and conductive band in conductors (left) and semiconductors (right)

To understand how the cell works, first consider how electrons in a metal flow. The outer most electrons reside in a collection of orbitals with nearly the same energy called the 'valence band.' These electrons are easily excited at room temperature into a collection of orbitals called the 'conductive band'. The conductive band is very close in energy to the valence band in metals so conduction is more likely to occur.[1b] See Figure 5 (left) A semiconductor, on the other hand, has a small energy gap between the orbitals of the valence band and the orbitals of the conductive band.[1b] See Figure 5 (right). Electrons in the valence band of the organic dye found in the cell will absorb a photon from incoming visible light. The energy of the incoming photon will excite an electron from the valence band to the conductive band.

The solar cell is built with a combination of two semiconductors. One, an organic material (in this case blackberry juice) and an inorganic material like titanium (IV) oxide. See Figure 6. Upon absorption of the photon from the sun, the electron in the organic dye's valence orbitals gets excited to the conductive orbitals of the dye. The electron is then transferred to the conductive band of the metal, a semiconductor with a larger band gap, usually titanium (IV) oxide and through the circuit to the load. The electron then flows to the other side of the circuit and is used to reduce iodine to iodide ($I_2 \rightarrow 2I^-$), which then loses the electron to the now positively charged dye, and thus the cycle repeats.

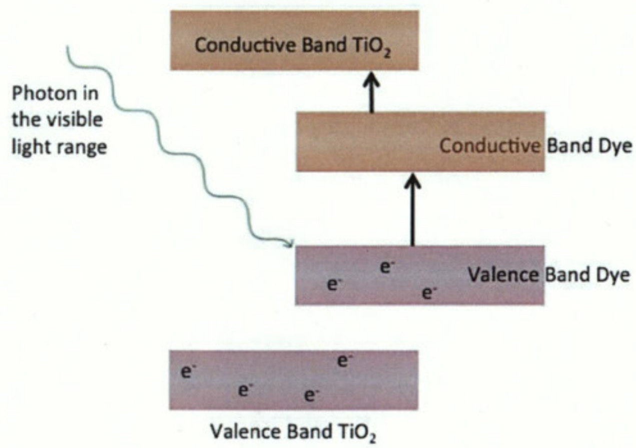

Figure 6: Electrons excited by photons move from the dye's valence band to the dye's conductive band, and finally to TiO_2's conductive band.

Procedure:

Gather all of the listed materials in "Juice from juice" by Jill Johnsen and Stephanie Chasteen.[3b]

<u>Day One:</u>

Part One: Preparation of Titanium (IV) oxide coated slides:

1. Weigh out 6 grams of TiO_2 and measure 10 milliliters of vinegar and combine in a mortar. Grind with the pestle until smooth. The solution should be able to be taken up with an eyedropper. Add one drop of detergent unless the solution becomes clumpy and mix.
2. Take half of the conductive slides and tape three edges of the slide to the table with the conductive side up. (The conductive side can be determined with a multimeter.)
3. Deposit three or four drops of the TiO_2 solution on the slide and spread with a glass rod to cover the entire non-taped surface of the slide.
4. If the slide is prefabricated, ignore this step. Bake the slides in an oven at a broil for one hour, or place them in a flame so that the white layer turns yellow and white again. This ensures the film is sintered onto the slide.

The slides can be stored in open air at this stage.

Part Two: Carbon-Coated Slide Preparation:

1. Cover the conductive side of the other slide with carbon via graphite stick or candle soot. The entire slide should be black.

Part Three: Electrolyte Solution Preparation:

If you cannot buy a premade Iodine/Potassium Iodide solution, you can make your own by combining 10 milliliters of ethylene glycol, 0.127 grams of iodine (I_2), and 0.83 grams of potassium iodide (KI) in a dark or opaque container.

Day Two:

Part Four: Staining the TiO_2 coated slides:

1. Crush ten blackberries and combine with one tablespoon of water, or thaw the juice left in the bag from frozen blackberries.
2. Put the dye solution in a dish with a flat bottom, so that the height of the fluid is at least half that of the slides.
3. Place the TiO_2 coated slides facedown into the dish and let them sit for ten minutes. When the slides are removed from the dye solution, there should be no white left.
4. Rinse the slides with water and ethanol or isopropanol and blot dry.

The slides should be used immediately, but can be stored in pH 3-4 acetic acid in a dark bottle if necessary.

(Possible Day Three)

Part Five: Assembly:

1. Place the slide so that the TiO_2 slide and the carbon-coated slide are together but offset so that alligator clips can be attached to each one.

2. Secure the slides together with two binder clips, ensuring the overhang points are unhindered.
3. Add a drop of the electrolyte solution to the gap between the slides. Ensure that the electrolyte stains the entire cell.
4. Attach the alligator clips and read the voltage in direct and indirect sunlight.

Part Six: Power to All:

1. First use your solar cell to make a small Christmas light run.
2. Try to make something larger, like a musical card or calculator, run. Does it take more than one?
3. What about a small fan?
4. The possibilities are limitless.

Experimental Notes:

- If using a flame to sinter instead of an oven, be careful. Some slides will shatter if heat is too concentrated in one spot.
- The slides read between 9.3 and 13.7 ohms before starting the experiment.
- In indirect sunlight, cells read between 0.47 and 0.13 volts.
- In direct sunlight, cells read between 0.82 and 0.25 volts.
- If the cell is reading below .24 volts, it will not be able to power a Christmas light.
- Place the cells in series to power larger objects.
- Place lights in parallel to power multiple at once.

Questions to Ask:

Question: What is the reactant and product in this reaction?

Answer: Photons, electricity

Question: If we assume that only visible light is being absorbed, what is the band gap energy?

Answer: Between 2.65 and 4.64 x 10^{-40} J

Question: How do we know UV light also gets absorbed?

Answer: The power output increases in direct sunlight as compared to behind a window.

Question: Why do we use the blackberry dye instead of just the TiO_2?

Answer: The TiO_2 on its own has a band gap too large to be excited directly by photons from the sun, but the dye acts as an in between step that the photons can excite the electrons to get across.

Prepared Worksheet and Answer Key Follows:

Name______________________________

1. Identify the reactant(s) and product(s) of the reaction.

2. Is the voltage produced by the cell larger or smaller in direct sunlight compared to indirect sunlight? Why?

3. If we assume that only visible light photons are being absorbed, what is the range of the band gap energy within? (λ_{red} = 700 nm, λ_{violet} = 390 nm) $c = \lambda\nu$ $E = h\nu$

4. Whose electrons are being excited by the photons?

5. Propose a set of oxidation-reduction reactions for this cell.

6. What was the voltage in indirect sunlight? Direct sunlight?

7. What was the current when a single light was connected in indirect sunlight? Direct sunlight?

8. What is the resistance of a single light bulb in both direct and indirect light? $V = IR$

Name **Key**

1. Identify the reactant(s) and product(s) of the reaction.

Photons, Electricity

2. Is the voltage produced by the cell larger or smaller in direct sunlight compared to indirect sunlight? Why?

Larger, UV-light is filtered by windows and also provides energy to the cell.

3. If we assume that only visible light photons are being absorbed, what is the range of the band gap energy within? (λ_{red} = 700 nm, λ_{violet} = 390 nm) $c = \lambda v$ $E = hv$

$c = \lambda v \rightarrow v = \frac{c}{\lambda}$

$E = h\frac{c}{\lambda}$

$E = 6.624\times10^{-34}\,\text{J/s}\left(\frac{3.00\times10^{8}\,\text{m/s}}{7.00\times10^{-7}\,\text{m}}\right) = 2.84\times10^{-19}\,\text{J}$

$E = 6.624\times10^{-34}\,\text{J/s}\left(\frac{3.00\times10^{8}\,\text{m/s}}{3.90\times10^{-7}\,\text{m}}\right) = 5.09\times10^{-19}\,\text{J}$

4. Whose electrons are being excited by the photons?

The dye's

5. Propose a set of oxidation-reduction reactions for this cell.

	forward	reverse
oxidation:	$dye \rightarrow 2e^- + dye^{2+}$	$3I^- \rightarrow I_3^- + 2e^-$
reduction:	$I_3^- + 2e^- \rightarrow 3I^-$	$dye^{2+} + 2e^- \rightarrow dye$
Overall:	$dye + I_3^- \rightarrow dye^{2+} + 3I^-$	$3I^- + dye^{2+} \rightarrow I_3^- + dye$

6. What was the voltage in indirect sunlight? Direct sunlight?

.34 Volts and .81 Volts.

7. What was the current when a single light was connected in indirect sunlight? Direct sunlight?

1.28 Amps 2.96 Amps.

8. What is the resistance of a single light bulb? $V = IR$

$V = IR \rightarrow R = \frac{V}{I}$

$R = \frac{.34}{1.28} = .26$ Ohms

$R = \frac{.81}{2.96} = .27$ Ohms

Safety and Storage:

- If any of the participants is allergic to raspberries/blackberries, do not attempt this cell. There is a kit by the Institute for Chemical Education (the same source for the organic kit described here) that is a nanocrystalline solar cell instead of an organic cell. It uses a similar iodine solution, so children allergic to iodine cannot make either of these options.[(2b)]
- Titanium dioxide is a slight skin irritant, wash with soap and water. If it is in contact with eyes, flush them with cool water immediately. Store in a cool dry space.[(12b)]
- Ethylene glycol is a slight skin irritant, wash with soap and water. Flush eyes with cold water if contact is made. If ingested, call a physician immediately. Store away from heat sources in a sealed container in a dry space.[(9b)]
- Potassium Iodide is a slight skin irritant. It should be stored in a dark or opaque container that seals tightly and keep in a cool environment.[(11b)]
- Iodine is extremely hazardous if it comes into contact with skin and eyes. Do not store above 77 degrees Fahrenheit in a tightly sealed dark or opaque container.[(10b)]
- Ethanol is slightly hazardous as a skin and eye irritant and should not be ingested. Do not store above 73.4 degrees Fahrenheit, and keep sealed and away from all sources of flame. If possible, store in a fire resistant space away from other materials.[(8b)]

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Activities for College Students:

It's the Berries: An Organic Photovoltaic Cell

Introduction/Background:

As solar energy is quickly making strides to becoming more popular, efficient, and more available, everybody will see the advantages of using this source of energy.[6c] There are many types of solar cells, the most common being a crystalline-silicon photovoltaic cell[4c, 14c], but the one outlined in this activity based on "Juice from Juice" by Johnsen and Chasteen is an organic photovoltaic cell (OPV).[3c]

To understand how the cell works, first consider how electrons in a metal flow. The outer most electrons reside in a collection of orbitals with nearly the same energy called the 'valence band.' These electrons are easily excited at room temperature into a collection of orbitals called the 'conductive band'. The conductive band is very close in energy to the valence band in metals so conduction is more likely to occur.[1c] See Figure 7 (left). A semiconductor, on the other hand has a small energy gap between the orbitals of the valence band and the orbitals of the conductive band.[1c] See Figure 7 (right). Electrons in the valence band of the organic dye

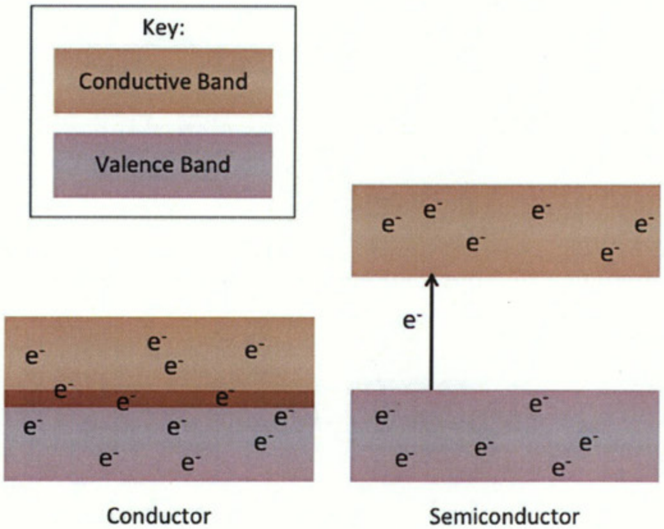


Figure 7: Energy gaps between the valence band and conductive band in conductors (left) and semiconductors (right).

ound in the cell will absorb a photon from incoming visible light. The energy of the incoming photon will excite an electron from the valence band to the conductive band.

Anthocyanins, found in the organic dye, are small gap semiconductors that have electrons that can be excited by visible light from the valence band to the conductive band.(6c) When a photon excites an electron to the conductive band, the electron leaves behind an empty space referred to as an electron hole.(15c) Another electron will fill the hole and form what is known as an exciton. The exciton will then split as another photon excites an electron and creates another hole for the electron to move to. As more photons excite electrons in a polymer, more holes will form, and non-excited electrons will move between them.(15c) See Figure 8.

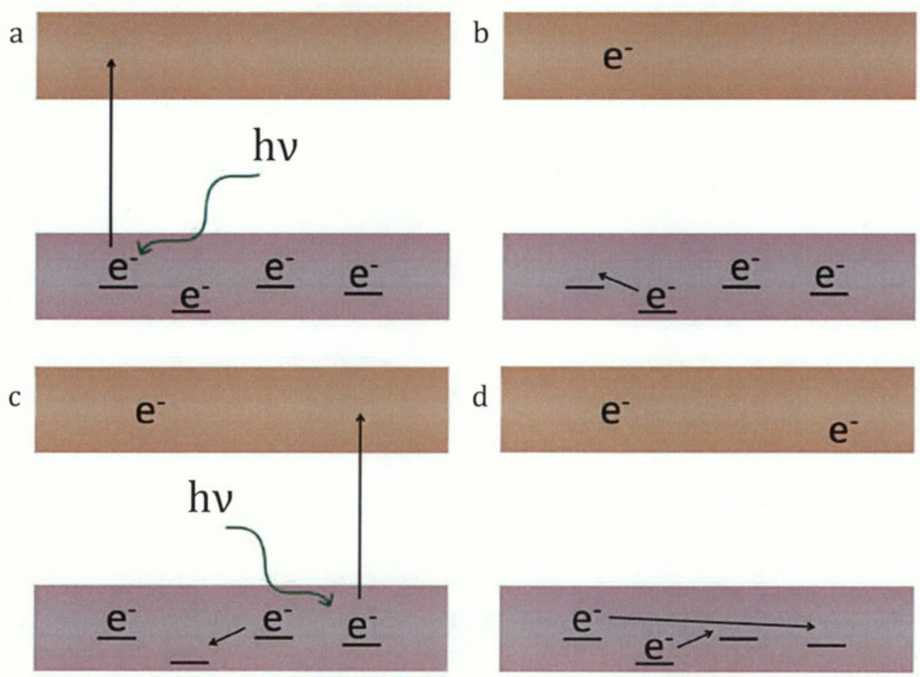


Figure 8 a,b,c, and d: Cycle of exitons being formed and split by electron excitation and electron movement to fill the holes in a valence band of a polymer.

This continuous movement by exciton formation is what produces an electric current. The electrons that get excited to the anthocyanin conductive band then move to the titanium (IV) oxide's conductive band and through the conductive glass to the load. It then returns to the carbon, a conductor, into the electrolyte solution.

The iodine is reduced to (tri)iodide and then the electron is transferred back to the positively charged dye's valence band.

Procedure:

Gather all of the listed materials in "Juice from juice" by Jill Johnsen and Stephanie Chasteen.(3)

Day One:

Part One: Preparation of Titanium (IV) oxide coated slides:

1. Weigh out 6 grams of TiO_2 and measure 10 milliliters of vinegar and combine in a mortar. Grind with the pestle until smooth. The solution should be able to be taken up with an eyedropper. Add one drop of detergent unless the solution becomes clumpy and mix.
2. Take half of the conductive slides and tape three edges of the slide to the table with the conductive side up. (The conductive side can be determined with a multimeter.)
3. Deposit three or four drops of the TiO_2 solution on the slide and spread with a glass rod to cover the entire non-taped surface of the slide.
4. If the slide is prefabricated, ignore this step. Bake the slides in an oven at a broil for one hour, or place them in a flame so that the white layer turns yellow and white again. This ensures the film is sintered onto the slide.

The slides can be stored in open air at this stage.

Part Two: Carbon-Coated Slide Preparation:

1. Cover the conductive side of the other slide with carbon via graphite stick or candle soot. The entire slide should be black.

Part Three: Electrolyte Solution Preparation:

1. If you cannot buy a premade Iodine/Potassium Iodide solution, you can make your own by combining 10 milliliters of ethylene glycol, 0.127 grams of iodine (I_2), and 0.83 grams of potassium iodide (KI) in a dark or opaque container.

Part Four: Staining the TiO_2 coated slides:

1. Crush ten blackberries and combine with one tablespoon of water, or thaw the juice left in the bag from frozen blackberries.
2. Put the dye solution in a dish with a flat bottom, so that the height of the fluid is at least half that of the slides.
3. Place the TiO_2 coated slides facedown into the dish and let them sit for ten minutes. When the slides are removed from the dye solution, there should be no white left.
4. Rinse the slides with water and ethanol or isopropanol and blot dry.

   The slides should be used immediately, but can be stored in pH 3-4 acetic acid in a dark bottle if necessary.

Day Two:

Part Five: Assembly:

1. Place the slide so that the TiO_2 side and the carbon-coated side are together but offset so that alligator clips can be attached to each one.
2. Secure the slides together with two binder clips, ensuring the overhang points are unhindered.
3. Add a drop of the electrolyte solution to the gap between the slides. Ensure that the electrolyte stains the entire cell.
4. Attach the alligator clips and read the voltage in direct and indirect sunlight/lamplight.

Part Six: Power to All:

1. First use your solar cell to make a small Christmas light run.
2. Try to make something larger, like a musical card or calculator, run. Does it take more than one?
3. What about a small fan?
4. The possibilities are limitless.

Experimental Notes:

- If using a flame to sinter instead of an oven, be careful. Some slides will shatter if heat is too concentrated in one spot.
- The slides read between 9.3 and 13.7 ohms before starting the experiment.
- In indirect sunlight, cells read between 0.47 and 0.13 volts.

- In direct sunlight, cells read between 0.82 and 0.25 volts.
- If the cell is reading below .24 volts, it will not be able to power a Christmas light.
- Place the cells in series to power larger objects.
- Place lights in parallel to power multiple at once.

Questions to Ask:

Question: What is an exciton?

Answer: An electron-electron hole pair

Question: What is the reactant and product in this reaction?

Answer: Photons, electricity

Question: If we assume that only visible light is being absorbed, what is the band gap energy?

Answer: Between 2.65 and 4.64 x 10^{-40} J

Question: How do we know UV light also gets absorbed?

Answer: The power output increases in direct sunlight as compared to behind a window.

Question: Why do we use the blackberry dye instead of just the TiO_2?

Answer: The TiO_2 on its own has a band gap too large to be excited directly by photons from the sun, but the dye acts as an in between step that the photons can excite the electrons up to so they can move to the conductive band.

Question: Identify the electron-rich areas of anthocyanins.

Answer: Alcohols and ketones

Prepared Worksheet and Answer Key Follows:

Name_______________________________

1. Identify the reactant(s) and product(s) of the reaction.

2. What is an exciton?

3. Is the voltage produced by the cell larger or smaller in direct sunlight compared to indirect sunlight? Why?

4. What was the voltage in indirect sunlight? Direct sunlight?

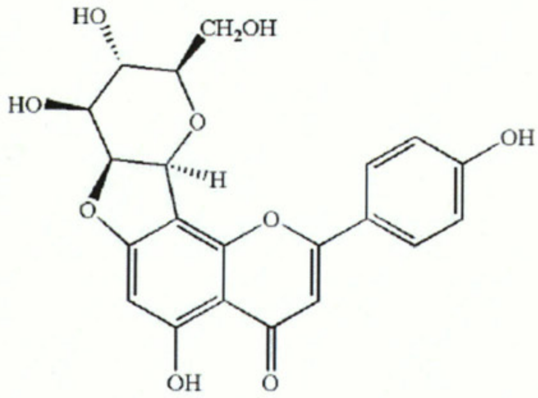
5. What was the current when a single light was connected in indirect sunlight? Direct sunlight?

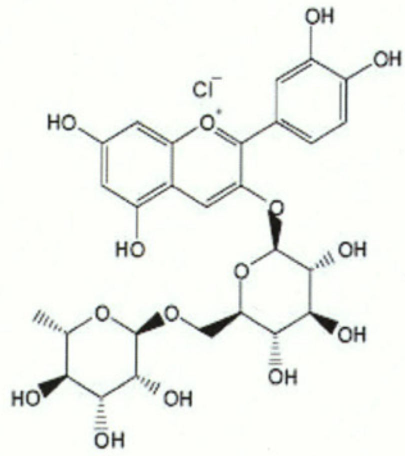
6. What is the resistance of a single light bulb in both direct and indirect light? $V = IR$

7. If we assume that only visible light photons are being absorbed, what is the range of the band gap energy within? (λ_{red} = 700 nm, λ_{violet} = 390 nm)

8. Whose electrons are being excited by the photons? Why those electrons over TiO_2?

9. Given the structure of the two anthocyanin molecules in blackberries, which functional groups must be present for the cell to work?





10. Propose a set of oxidation-reduction reactions for this cell.

Name Key

1. Identify the reactant(s) and product(s) of the reaction.

Reatants: photons   Product: electricity

2. What is an exciton?

An exciton is an electron and electron hole pair formed in the valence band when another electron is excited to the conductive band from the valence band by absorbing energy from a photon.

3. Is the voltage produced by the cell larger or smaller in direct sunlight compared to indirect sunlight? Why?

Larger, because windows prevent UV light from passing through, and UV light is higher in energy than visible light. The anthocyanin used will absorb photons in both parts of the electromagnetic spectrum.

4. What was the voltage in indirect sunlight? Direct sunlight?

Indirect: 0.34 Volts

Direct: 0.81 Volts

5. What was the current when a single light was connected in indirect sunlight? Direct sunlight?

Indirect: 1.28 Amps

Direct: 2.96 Amps

6. What is the resistance of a single light bulb in both direct and indirect light? $V = IR$

$$V = IR \rightarrow R = \frac{V}{I}$$

Indirect: $R = \frac{0.34 \text{ Volts}}{1.28 \text{ Amps}} = 0.26 \text{ Ohms}$

Direct: $R = \frac{0.81 \text{ Volts}}{2.96 \text{ Amps}} = 0.27 \text{ Ohms}$

7. If we assume that only visible light photons are being absorbed, what is the range of the band gap energy within? (λ_{red} = 700 nm, λ_{violet} = 390 nm)

$c = \lambda \nu$ and $E = h\nu$

$\nu = \frac{c}{\lambda} \longrightarrow E = h\left(\frac{c}{\lambda}\right)$

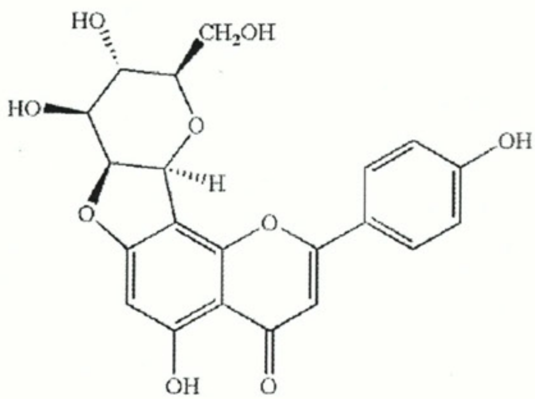
Red: $E = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}\left(\frac{3.00 \times 10^{8} \text{ m/s}}{7.00 \times 10^{-7} \text{ m}}\right) = 2.84 \times 10^{-19} \text{ J}$

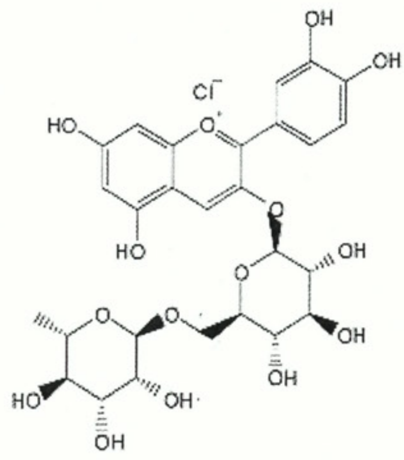
Violet: $E = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}\left(\frac{3.00 \times 10^{8} \text{ m/s}}{3.90 \times 10^{-7} \text{ m}}\right) = 5.09 \times 10^{-19} \text{ J}$

8. Whose electrons are being excited by the photons? Why those electrons over TiO_2?

The dye's (anthocyanin) electrons were excited by the photons instead of titanium (IV) oxide's electrons because the band gap in the dye is smaller than the band gap in TiO_2.

9. Given the structure of the two anthocyanin molecules in blackberries, which functional groups must be present for the cell to work?





Alcohols (ketones also work)

10. Propose a set of oxidation-reduction reactions for this cell.

$$\text{dye} \rightarrow 2e^- + \text{dye}^{2+} \quad \text{oxidation}$$

$$I_3^- + 2e^- \rightarrow 3I^- \quad \text{reduction}$$

$$\text{dye} + I_3^- \rightarrow \text{dye}^{2+} + 3I^-$$

Safety and Storage:

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